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(54) **Keratometer/pachymeter**

(57) A video Keratometer/Pachymeter comprising an array of illuminated points disposed in concentric circles around the optical axis of a television camera for definition of corneal surface contour by a method similar to the well know Placido, except that the isolated point ring format provides unambiguous back ray trace information to eliminate errors inherent in the prior art, in combination with a projected pattern of discrete points to elicit Tyndall images for definition of both anterior and posterior corneal surface by triangulation using multiple television cameras viewing the reflected and Tyndall images, substraction of a view of the eye with neither pattern superimposed as well as each pattern in sequence for isolation of the data containing points from the general clutter of background pictorial information.

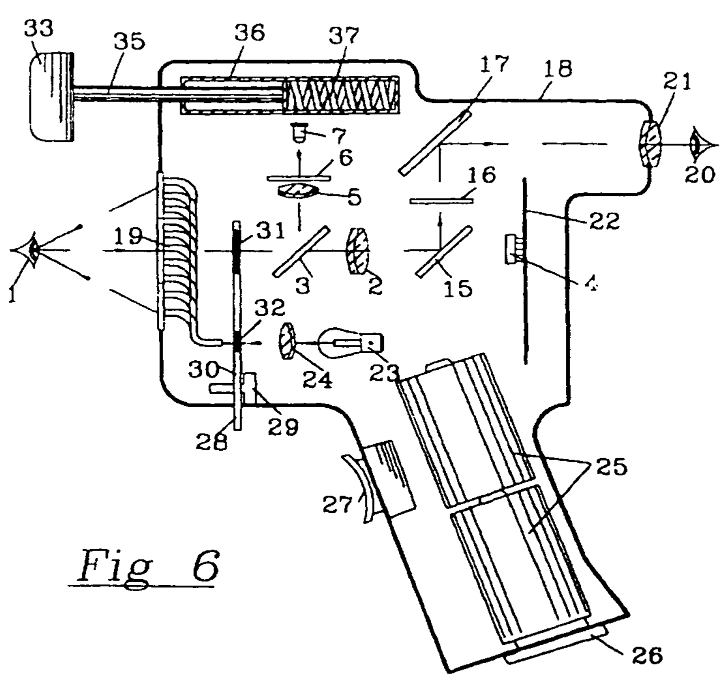


*Fig 6*



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## BACKGROUND OF THE INVENTION

### 1. Field of the Invention

[0001] The present invention relates to improvements in the art of photo-keratometry and pachymetry and, more particularly, to the use of television techniques to ascertain the contour and thickness of the cornea. A pachymeter is an instrument for measuring the thickness of the cornea, commonly by ultrasound or optical devices. A keratometer is an instrument for determining the shape of the corneal surface which often uses a placido or other illuminated target which is reflected from the surface to be characterized for surface contour. The present invention measures both the keratorefractive surface shape by a modification of Placido's device coupled with a photo triangulation Tyndall image analysis method for determining the corneal thickness.

### 2. Brief Description of Related Art

[0002] U.S. Patent No. 3,797,821 discloses the use of a camera to record the placido reflex from a patient's eye. From this photograph, the radius of surface of curvature of the cornea is determined at several points which is calculated using a complex computer system. The use of a ground glass focusing screen with the small aperture of the optical system and large linear magnification makes use difficult and requires a darkened room for operation. Additionally, the method utilizes a separate video/computer analysis step which further degrades accuracy, speed and increases cost of operation. More recently, U.S. Patents, such as U.S. Patent No. 5,841,511 to D'Aousa, et al, have addressed the problem of the inherent ambiguity of the concentric circle form of the Placido while U.S. Patent No. 5,847,804 to Sarver, et al attempts to define the corneal apex through the use of an additional camera which purports to locate the apex and limbus.

[0003] U.S. Patent No. 4,440,477 discloses a method and device for measuring the corneal surface, comprising a slit lamp for illuminating the corneal surface, a camera for recording the reflection from the corneal surface, and a processor to calculate the image distance and the radius of curvature of the eye. Additionally the prior art devices do not work well in the presence of reflections from objects or lights in the room and do not provide rapid, accurate measurements such as are required for modern contact lens fitting.

[0004] The traditional approach to photogrammetry has bene very software intensive and, thus, quite costly. The most common technique is to convert the entire television image to digital form prior to sorting, calculating by matrix algebra techniques, and display. The digitized image must occupy only a portion of the available memory in any computer system if there is to be the capacity to act upon the image information. More recent technique are described in my U.S. Patent Nos. 5,110,200 and 4,412,965, as well as Gersten's work such as disclosed in U.S. Patent No. 5,384,608. The present invention addresses some of the problems found with the prior art.

[0005] When photographs of the reflections of Placido's disc are made the contour of the cornea is such that only the middle zone can be measured since the more peripheral zone is sloped in such a way as to prevent the reflected image to be seen to be a centrally located camera. The central zone is not resolved because the size of the reflection approaches the inherent resolution of the camera employed and the error of determination increases to infinity at the center of the image being analyzed. Measurements of the ring reflections by back tracing rays assumes that the exact point of origin of a ray from a continuous line can be made which is clearly not possible. Because there is no possible measurement at center, even if the reflection of a fixation target is assumed to define the corneal apex, the exact location of the image plane behind the corneal surface and the true apex are unknown. However, both of these must be known for accurate measurement results. Back tracking rays can define the tangent slope of points on the cornea to a fair degree of accuracy, but only if the initial point used in the constructing the surface model is known which is not possible in simple Placido based designs. A keratometer based on Placido's method can only measure anterior surface curvature in terms of radius of curvature at selected points. Because the posterior surface of the cornea in conjunction with the aqueous film constitutes a negative lens, the effective dioptric power is the algebraic sum of the two "lenses". For the keratometric measurement to be strictly accurate, the corneal thickness must be constant, known and perfectly concentric on both the anterior and posterior surfaces. For example, the common Bausch. & Lomb keratometer used in most clinical settings uses a biased value of index of refraction in the conversion from radius of curvature to dioptric form to compensate for this problem. My recent Patent Nos. 5,885,767 and 5,735,283 describe apparatus and method for determining the needed information but have an inherent limitation caused by distortion of the projected image points by both surface slope and corneal thickness at the point of reflection.

## BRIEF SUMMARY OF THE INVENTION

[0006] There is provided herein a new teaching for video image analysis that provides lens or cornea topographical maps of the surface contour and thickness with almost instant display of the data for clinical use.

[0007] The improved photo keratometer/pachymeter of this invention comprises: an illuminated target or so-called placido formed of a plurality of small circular illuminated points, preferably disposed in concentric circles around the optical axis of the instrument, which are re-

flected by the surface to be examined, a television camera and lens system mounted by a modified bean splitter assembly to obtain the image of the surface being examined, a projection system for providing a plurality of Tyndall images in essentially circular form, plural television cameras for capturing the reflected and projected image elements for analysis defined, a conventional electronic computer to derive the surface contour of the eye and to generate the display of the derived shape information for use, and a computer display and a system for aligning the optical axis of the eye with the measuring axis of the instrument.

[0008] The video output for general use and recording may be obtained from the present invention, if required. The keratometer/pachymeter system of the present invention makes use of a "bus-card" in a PC type microcomputer to provide fast and accurate measurements without the apparatus associated limitations of the other available systems. With careful use the system will consistently provide information to the lens manufacturer or optometrist to quantify surface shape of contact lenses in addition to measurements of the cornea. Several computer generated data display formats can be made available from a numerical axis and magnitude scale in the eyepiece to computer monitor displays such as a vector map with a line indicating both axis and magnitude against a series of concentric circles representing cylinder magnitude to permit rapid assessment of astigmatism and to permit the user to select a lens which will result in the best corrected vision for the patient. The preferred configuration provides a small hand held device with connection to an external computer.

## BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Having thus described the invention in general terms, reference will now be made to the accompanying drawings in which:

- Figure 1 is a schematic view which illustrates the limitation of peripheral measurement of Placido's method;
- Figure 2 is a schematic representation of the eye showing the difference between the line of gaze and the optical centerline of the eye;
- Figure 3 is a block diagram of the major elements of the present invention;
- Figure 4 depicts the movable fixation target employed in the system of the invention;
- Figure 5 shows the raypaths for generation of Purkinje images in the eye;
- Figure 6 illustrates a cross sectional view of one embodiment of the invention;
- Figure 7 is a partial front view of the instrument of the invention;
- Figure 8 illustrates the projection illumination system in the instrument of the invention;
- Figure 9 is a cross sectional view of the preferred embodiment of the present invention: and
- Figure 10 is a schematic block diagram showing some of the major components forming part of the circuit used in the system of the present invention.

## DETAILED DESCRIPTION OF A PREFERRED EMBODIMENT

[0010] Referring now in more detail and by reference characters to the drawings, and presently to Figure 2, there is a small area of the retina in which there is a concentration of the cone type photo-receptor cells which are synapsed on an almost one to one ratio with nerve fibers. This central vision area is termed the fovea. It is at the fovea that the critical vision associated with reading and similar optical tasks takes place. The optical axis of the eye does not coincide with the fovea, but rather is displaced by five to seven degrees. The main light focusing power of the eye is contained in the cornea and the fluid filled anterior chamber in front of the crystalline lens.

[0011] Figure 1 illustrates one of the principal limitations of Placido based measurements. The focal length of a convex mirror is one-half of the radius of curvature and the image and object sizes can be related to the focal length. The object in this case may take the form of a placido or Placido's disc. The placido is commonly in the form of a trans-illuminated surface of translucent material with opaque concentric rings. The target is illuminated by one or more lamps placed behind the disc surface so the translucent areas are bright circles as viewed by the subject. A simplified ray trace is shown where a known point on a circle, A is reflected from the cornea along a part ABC which enters the camera lens located at C. A surface normal at the point of reflection will form equal angles and DBC and an extension of the bisector from D will intersect the axis at some point. If, however, the peripheral cornea has a surface slope, as shown, the ray from some point E will be reflected along a path EFG which will not enter the lens of the camera. Consequently, peripheral areas of the cornea cannot be measured by this technique.

[0012] A television camera with adequate sensitivity and resolution is installed by means of a conventional beam splitter and camera mount attachment to the biomicroscope to generate the electronic image of the reflection to be analyzed.

[0013] It is obvious that as the angle of the reflection relative to the optical axis increases, with an object size increase at a fixed distance, the amount of deviation from the paraxial computation must also increase at a faster rate. That is to say that the angle subtended by each successive placido ring is not constant. To provide for this optical aberration induced error of calculated curvature of the cornea, a table is used to compensate the calculation for the amount of curvature and the object size, and consequently, angles from the eye surface to the optical axis. It follows that the table value must be a

compromise in that the image must subtend a finite width to be visible and, in consequence, the various portions of the image are displaced by slightly different amounts. The table values are derived from measurements made from spherical objects of known diameter. The derived data are in the form of spherical equivalent curvature at the various distances from the assumed optical center and as such are not strictly a true surface shape. The keratometer of common use measures two perpendicular meridians at each selected angle and produces data in the form of "K1,K2", Cylinder and axis. These terms refer to the average dioptric curvature in the two axes which have the greatest and least curvature, assumed to be 90 degrees apart or, "regular" astigmatism. The magnitude of the difference between K1 and K2, and the angle relative to the horizontal of the larger of the two are terms which are commonly used and are recognized by the user as definitive of these descriptive elements, as derived by conventional keratometry. The axis can either be measured or assumed to be regular (90 degrees apart) in the case of contact lenses where the astigmatic curvature is, in general, mechanically generated as a toric or spherical section only.

**[0014]** Referring now to Figure 2, the so-called Purkinje images are simply reflections of a small fraction of the incident light at each interface where there is a change of index of refraction of the media through which light passes. If the ray enters along the axis of rotational symmetry, all of the surfaces encountered would be exactly perpendicular to the ray path and the reflections would be coincident when viewed along the line of propogation. If, however, the ray A enters at some other angle, the existing reflected light would follow different paths from each interface. When the ray from A strikes the corneas 9 at an oblique angle, the reflected ray would travel along a different path 12. A majority of the light would continue through the cornea and again be slightly deflected before reaching the anterior surface of the lens 10 where the existing reflection would be along a different path 13. Again, the bulk of the light would pass into the lens and at the posterior surface there would be another reflection along a path 14 different from the previous exit paths. In the present invention, the fixation target is imaged at optical infinity for this reason. The measurement of anterior chamber depth can only be valid when the subject is not accommodating and so the design of the fixation target system is structured to inhibit the focus reflex.

**[0015]** Turning now to the block diagram, Figure 3, a computer 38 of the conventional design which may be remote rom the instrument provides control, timing data acquisition, analysis and display for the system. Three television cameras 4 are disposed to provide coincidence of their optical axes at a defined point slightly behind the expected location of the eye to be measured 1. Cameras 1 and 2 provide oblique views at equal angles, preferably thirty degrees from the optical axis 40 of the central camera, camera 3. These cameras provide a stereoptic view of the eye and any reflected or projected pattern thereon for defining the location in three space of the projected or reflected pattern elements. The central camera, camera 3, provides an axial view for the typical Placido type pattern analysis and also serves as a viewfinder to permit the operator to bring the Purkinje reflections into total or near coincidence to establish the axial relationship between the eye 1 and the instrument. A pseudo-placido (not illustrated for clarity) is disposed around the projector lens 44 which also serves to provide an image of the eye 1 to camera 3 4. In addition, the lens 44 allows projection of a reticle 43 illuminated by a lamp 45 and a condenser lens 24 for projecting a pattern of small spots onto the cornea to elicit the Tyndall images from diffuse reflection within the bulk of the cornea. In operation, the projector lamp 45 and the Placido illuminating lamp are extinguished while the operator positions the instrument against the head of the subject with centering of the image of the eye 1 to be examined and the fixation target positioned to bring the Purkinje reflections into coincidence.

**[0016]** Reflections from the several optical surfaces of the eye were first described by Purkinje in 1823 ND Sanson in 1837. During an eye examination, these catoptric images are formed at each optical discontinuity when the eye is illuminated with an ophthalmoscope of either the direct or indirect type. They are akin to the reflections used for centering and aligning the several elements of an optical system. However, the bright reflection from the anterior surface of the cornea, actually the tear film on the corneal surface, is much brighter than the reflections from more posterior surfaces. This is due to the large step change in refractive index at the surface from air to the tear film with a R.I. of about 1.334. In order to see the more distant dimmer reflections, the focal illumination system is offset from the viewing axis. The image of the filament of a small bulb is reflected either by a small mirror or a prism located just below the viewing axis of the instrument. All of the common clinical viewing instruments, such as the slit lamp, direct and indirect ophthalmoscopes, and surgical microscopes, are constructed with slightly off axis illumination so that the bright reflection of the illumination source does not mask the other central reflections and more posterior Purkinje reflections. From the observations made with these instruments, the physician is taguth that the so-called "Purkinje images" cannot be superimposed.

**[0017]** The images from the television cameras are in exact temporal synchronism through the action of the Pulse Shaper 39 from a computer providing timing signal complex. This assures that all of the television information is free of motion artifact. The three most recent frames of this background image series are always placed in rotating storage in the computer. When the operator has aligned the instrument and fixation target, he operates a switch to initiate data gathering. On the next vertical blanking interval, the placido illumination lamp

is illuminated for a short time to generate three simultaneous pictures of the reflections from the cornea. These are converted to digital format and stored in another location in the computer memory for analysis. At the time of the next successive vertical blanking pulse, the Placido illumination is off and the projection lamp 45 is flashed in synchronism with the television camera control to provide an additional trio of images for analysis. The image data are amplitude normalized in the computer and the averaged value of pictorial information from the three frames, prior to operation of the start switch, are subtracted on a pixel by pixel basis from the second and third exposures with different illumination. The result of the subtraction and thresholding is to remove any pictorial information from the two sets of data containing exposures. This process is disclosed in detail in my other U.S. Patent Nos. 5,735,283 and 5,886,767.

**[0018]** In order to align the instrument axis with the axis of best symmetry of the eye provision is made for adjusting the location of the fixation target relative to the optical centerline of the instrument. As the subject focuses on the fixation target, any displacement of the target will cause movement of the eye relative to the optical axis of the instrument. As the operator monitors the Purkinje images he manipulates the fixation target position in the instrument which causes the eye to rotate in such a way as to bring about the desired alignment, Figure 4 illustrates the operation of this feature of the present invention. The optical axis of the camera 4 and the eye 1 are not initially aligned. The image of the eye 1 is centered in the image by positioning the entire instrument relative to the subject's head and brought into proper focus by axial movement of the instrument relative to the subject. The subject is then able to see the fixation target at optical infinity through the action of the lenses 2 and 5. While monitoring the Purkinje reflections, the operator moves the target 6 illuminated by a lamp 7. The viewing path 40 by way of a beam splitter 3 permits simultaneous viewing of the eye 1 by the operation and the fixation target 6 by the subject. As the operator manipulates the fixation target control, the target 6 moves in the focal plane of the lens 6 and the line of gaze of the subject's eye 1 is caused to move in a corresponding manner. At some point, the dispersion of the Purkinje reflections are observed to be at a minimum indicating that the optical axes of the eye 1 and the camera 4 are coincident. At that time, the operator presses the switch initiating the lamp control sequence and attendant capture of the data containing image sets for computer analysis.

**[0019]** Figure 8 illustrates the relative location of the major optical elements in an alternative embodiment of the present invention. A television camera 4 with an associated lens 34 is disposed on the folded optical axis of the instrument. Through the action of a pair of beam splitters 3 and 15 the erect magnified image of the eye 1 being examined is focused on the photo sensitive matrix of the camera 4 by positioning the entire instrument relative to the subject. An alignment reticle and/or split image rangefinder prism (not illustrated) of conventional design may be included in this optical path if desired to facilitates the alignment and focus step. After alignment of the instrument and the fixation target 6, the operator presses a switch and the associated computer causes the strobe tube 46 to be fired in temporal synchronism with the television timing signal. The very short illumination time provides a motion artifact illumination of a pattern of points on a reticle 47 which is imaged at the cornea of the eye 1. This image is captured by the associated computer system by well known apparatus and method for producing a digital record of the eye 1 with the pattern superimposed. A filter 48 which is transparent to near infrared light from the lamp 45 prevents disturbing light to be visible to the subject while still providing adequate illumination for the camera 4 which is sensitive to those wavelengths. An additional incandescent lamp 45 is imaged at the center of the strobe tube 46 by a condenser lens 47 so that either lamp may provide the illumination for the system. This permits the operator to select the second illumination system for judging the alignment of the instrument. The central location of the camera 4 provides an undistorted view of the reflection of a pseudo-placido system reflected by the corneal surface of the eye 1 to obtain the conventional Placido type data in the sequence of operations initiated by the user.

**[0020]** Figure 6 illustrates the general arrangement of the preferred embodiment. The instrument is contained within a unitary housing 18 provided with a handle which may serve to contain batteries 25 for providing electrical power for operation of the instrument. The batteries 25 may be replaced via a removable cover 26 of conventional design. A brow rest 33 is contoured to rest against the forehead of the subject. In operation, the user places the brow rest 33 against the surface of the forehead of the subject and, by applying pressure on the handle, causes the support shaft 35 to compress a spring 37 located within a suitable housing 36. The shaft 35 may be provided with a hinge or other compliance member so that the brow rest conforms to the contour of the subject's face to eliminate any discomfort to the subject. Small lamps 50 (see Figure 7) adjacent to the camera lenses 34 illuminates the eye 1 to be examined as the operator moves the entire instrument to cause the image of the eye 1 to be centered in the eyepiece 21. The image of the eye is conveyed to the eyepiece for this purpose by means of beam splitters 3 and 15, a focus aid split image rangefinder plate and prism system 16 and a mirror 17. As the instrument is centered, axial motion will cause the central portion of the image to seem to merge through the well known action of the said rangefinder prism.

**[0021]** By further reference to Figure 6, it can be observed that a pivotal sheet 30 is supported on a bearing/switch assembly 29 so that a handle 28 can be manipulated by an operator of the device. The handle can be operated to position a pair of filters 31 and 32 to be lo-

cated within the optical path. This pair of filters 31 and 32 provides the color of the illuminating light from the lamp 23 and through a condenser 24. In this way, the points to be reflected from the corneal surface are lighted.

**[0022]** Simultaneously therewith, one of the filters 31, which serves as a barrier filter, is placed in the return path to band-stop the reflected light and eliminate direct light through the other of the filters 32 which functions as an exciter filter. As an example, the filter 32 may be a blue filter and filter 31 would be a yellow filter and this combination would be used for florescence to depict only the anterior surface of the cornea coated with a dye.

**[0023]** The switch 29 adjusts the light 23 and the camera exposure to compensate for the losses caused by the existence of the filters 31 and 32 in the optical path. These filters 31 and 32 can also be used to enhance the illumination to balance the brightness of the frame center/edge which falls off quickly from the center in the amount of diffuse reflected light reaching the camera 4.

**[0024]** When the instrument is properly positioned with the image of the eye 1 centered and focused, the operator manipulates a control (not illustrated) of conventional design whereby the fixation target 6 is caused to move in the horizontal plane. At some point the Purkinje images are brought into close or total convergence. At this time, the operator presses the switch 27 to initiate the date acquisition.

**[0025]** The television cameras 4 are operating continuously during the alignment phase as well as the data gathering phase of the operation of the instrument and, prior to the operation of the switch 27, one or more images taken simultaneously by the cameras is held in storage in digital form within the associated computer for later comparison with the data containing image sets. After the operation of the switch 27 by the operator, the Placido illumination lamp 23 via a suitable lens 24 and a number of optical fibers 19 causes the illumination of a plurality of small discrete points of known location to be illuminated.

**[0026]** The reflection of these illuminated concentric circles of illuminated points from the surface of the eye 1, together with the image of the eye as illuminated by the lamps 50, is observed by the television cameras 4 and a single frame from each camera is simultaneously captured and stored in the associated computer memory for analysis. On the next subsequent television frame, the Placido illumination lamp 23 is extinguished and the reticle projection lamps, not shown, is illuminated causing another set of simultaneous images to be captured in the computer memory in digital form for analysis.

**[0027]** The pseudo Placido containing date frame information from the television frame is recovered in the computer as is the average of the non-data carrying frame or averaged frames recorded prior to the operator of the switch 27. By a well known process of normalization, substraction and thresholding, the reflections of the plurality of pseudo Placido points is recovered and stored for analysis. By the same process, the second group of television images containing the Tyndall images produced by projection of the reticle 47 image are similarly recovered and stored.

**[0028]** Some of the components which form part of the computer 38 and some of the associated components operable thereby are more fully illustrated in the schematic block diagram of Figure 10 to show the cooperative relationship therebetween. In this case, it can be observed that the computer 38 comprises, among other operative components, a main processor 60 and a sequencing section, or so-called sequencing means 62, for operating the projector. In this way, the projector can take sequential images. The computer also includes, at least schematically, an image point isolation circuit in the form of an image point isolation means 64 and which isolates the reflected and direct images of the points. It can be observed that the three cameras 4 are also operable in synchronous timed relationship by means of a timer 66 and which may, in turn, be operable from the computer processor 60. It can also be observed by reference to Figure 10 that the processor receives an electrical analog signal from each of the cameras 4. In this way, the computer receives and processes electrical analog signals of the images from each of the cameras.

**[0029]** In the present invention, the illumination and viewing optical systems are made truly coaxial and a small occluder spot of neutral density filter material is cemented to the reticle used for alignment. This reduces the brightness of the central reflection to the extent that the Purkinje images may be very closely aligned when the instrument is being adjusted to capture the images to be used for map construction. In a paper delivered at the American Association of Ophthalmology meeting in 1998, Dr. T. Turner Ph.D. of Orbtek, Inc. stated that the eye contains de-centered and tilted image forming surfaces and consequently light rays do not traverse the straight lines dictated by the common laws of physics. From his "discovery that the Purkinje images cannot be aligned", he concludes that the optical elements of the eye must be tilted, de-centered or both. This opinion is reinforced by the fact that the fovea is not located on the axis of best symmetry of the optical system of the eye so the line of gaze or fixation axis when looking at a distant point source is offset by about six degrees from the centerline of the system. The fovea where critical central vision takes place is offset from the optical axis of the eye by about five degrees so image quality at the fovea is assumed to be defined by the perceived asymmetry of the optics.

**[0030]** Clearly, however, if the image formed at the retinal surface is adequately sharp to resolve the Snellen test figures, the optics system of the eye must be fairly close to rotational symmetry. The eye chart figures devised by Snellen comprises a five by five element matrix of twenty-five square elements which each subtend one minute of arc at the viewing distance of twenty feet or

six meters. The limitation imposed on the resolving power of the ametropic eye is the packing density of the receptor cells in the fovea centralis where critical images form the center of our visual field. Electron microscopy shows that the individual cells are about one micron in diameter and are packed in a nearly hexagonal manner. From this it follows that the choice made by Snellen was a rational one. Using classical Airy-Rayleigh relationship analysis of the image of a distant point source, light at a wavelength of 555 millimicrons via a three millimeter pupil should form the first dark ring with an angular subtense of about 47 arc seconds or about 0.004 millimeters in diameter. This figure agrees well with the observed packing density of receptor cells in the fovea and provides a definition of best contour acuity in the "normal" ametropic eye. However, there is also the phenomenon of "vernier acuity" which defines the ability to see a discontinuity in a line. This is much smaller and is influenced by the time of observation so we may conclude that some averaging is taking place in the visual processing system of the brain.

**[0031]** Referring now to the cross sectional view of the preferred embodiment, Figure 9, the reticle projection system comprises a lamp 45, a condenser lens 24, an apodizing filter 48, a reticle 47 and a projector lens 2. The image of the reticle 47 is focused on the eye 1 and when the lamp 45 flashes, the plurality of illuminated points so produced on the cornea of the eye 1 produces a plurality of Tyndall images which contain not only surface contour information but also corneal thickness information. A small display 49 such as is used for a viewfinder on small videotape cameras is made viewable through a lens 21 for providing the operator a television image from the central camera suitable for performing the centering, focus and Purkinje image alignment steps. The television images from the cameras 4 are again captured and stored for analysis, as described above.

**[0032]** The pseudo-placido disc is constructed in the conventional manner except that in lieu of a set of concentric circles of translucent material, the pattern is divided into a plurality of circular translucent areas arranged in concentric circles. The illuminated spots to be reflected by the cornea are sized to provide five or more pixels of subtense in the captured image with a separation of at least twice the illuminated diameter. These provide a basis for accurate back tracing the rays without the ambiguity inherent in a continuous circular form of Placido rings of the prior art to eliminate one of the error sources of those devices. Analysis of the isolated points produced in the image subtraction step produces a large number of locations on the corneal surface for which the surface slope is known. The projected image of the reticle is distorted by the surface slope of the cornea at the point of the projected spots and the Placido derived data are then used to define and eliminate this distortion from the reticle projection derived images. The spots as so derived are not circular due to the diffuse reflection within the bulk of the cornea but with the surface shape induced distortion removed, the centroids of the "blob" can be accurately defined to provide the basis for definition of the local corneal thickness. Triangulation from the plural images produced by the projection system provides an accurate method for defining the now central corneal apex by the action of Purkinje image alignment. This, in turn, provides the vital but missing information from the Placido based systems of the prior art to significantly enhance the accuracy of the surface contour data derived from the Placido reflection step and this, in turn, provides a more accurate data base for analysis of the pachymetric and contour data derived from the reticle projection system.

## Claims

1. An improvement in a method for measuring physical parameters of a cornea for clinical diagnostic purposes in which a pattern of isolated points is projected on said cornea, the improvement in said method comprising:

   a) reflecting from said cornea said pattern;
   b) producing a plurality of sequential images of the said cornea from a camera means;
   c) isolating the images of each of the plurality of reflected and projected points;
   and
   d) defining the surface contour and thickness of said cornea from said projected and reflected image points.

2. The improvement in the method of Claim 1 wherein said method comprises producing the sequential images from a plurality of cameras which comprises said camera means with each comprising a camera array and detector array, two of said cameras disposed at equal angles to the axis of projection of the said projector, and a third camera for forming an image of the eye located centrally with an optical axis coincident with said projector.

3. The improvement in the method of Claim 2 wherein the method simultaneously measures surface shape and thickness of the cornea.

4. The improvement in the method of Claim 2 wherein said method comprises assuring temporal synchronism between all of the said cameras, and alignment of the optical axes of the said cameras aligned to intersect in a common point located slightly beyond said cornea.

5. The improvement in the method of Claim 2 wherein the method comprises controlling the illumination of the eye indirectly and with the projected and reflect-

ed patterns disposed on the cornea sequentially with a sequencing means.

6. The improvement in the method of Claim 2 wherein said method comprises establishing by triangulation the location in three dimensions of each of the said plurality of image points and reflecting points.

7. An instrument for measuring physical parameters of a cornea for clinical diagnostic purposes comprising an optical projector (44) which projects a pattern on the cornea and camera means (4) producing a plurality of sequential images of said cornea, an improvement comprising:

   a) the pattern projected on the cornea is of isolated points, and an illuminated target that can be reflected from said cornea, said pattern also comprising a plurality of isolated points;
   b) said camera means (4) comprising a camera array and detector array, said camera means being aligned to cause images to said camera array to intersect in a common point located slightly beyond said cornea;
   c) a computer (38) receiving the electrical analog of the images at said camera means; and
   d) means (38) utilizing the electrical analog of said images for defining the surface contour and for defining the thickness of said cornea from at least said projected points and reflected image points.

8. The improvement in the instrument for measuring surface shape and contour of Claim 1 the instrument simultaneously measures surface shape and thickness of the cornea and wherein said camera means comprises at least three cameras (4), two of said cameras disposed at equal angles to the axis of projection (40) of said projector (44), and a third camera for forming an image of the eye located cetrally with an optical axis coincident with said projector.

9. The improvement in the instrument for measuring surface shape and contour of Claim 8 wherein said instrument comprises an illuminated target (7) disposed for viewing by the subject of examination through the centrally located camera lens, said target being movable in the focal plane of the said lens perpendicular to the axis of view for establishing a desired relationship between the several reflections of said target.

10. The improvement in the instrument of Claim 7 wherein the device is a hand-held keratometer/pachymeter device capable of measuring a surface shape and a thickness of a cornea for diagnostic purposes, and wherein said device further comprises:

   a) an outer housing;
   b) light generating means within said housing for projecting said pattern of isolated points on the cornea of an eye being examined;
   c) said camera means being located within said housing and being arranged to be aligned with the cornea and intersect at a common point behind the cornea and thereby produce the plurality of sequential images thereof: and
   d) an optical path including optical elements for causing an image of reflected isolated points on the cornea.

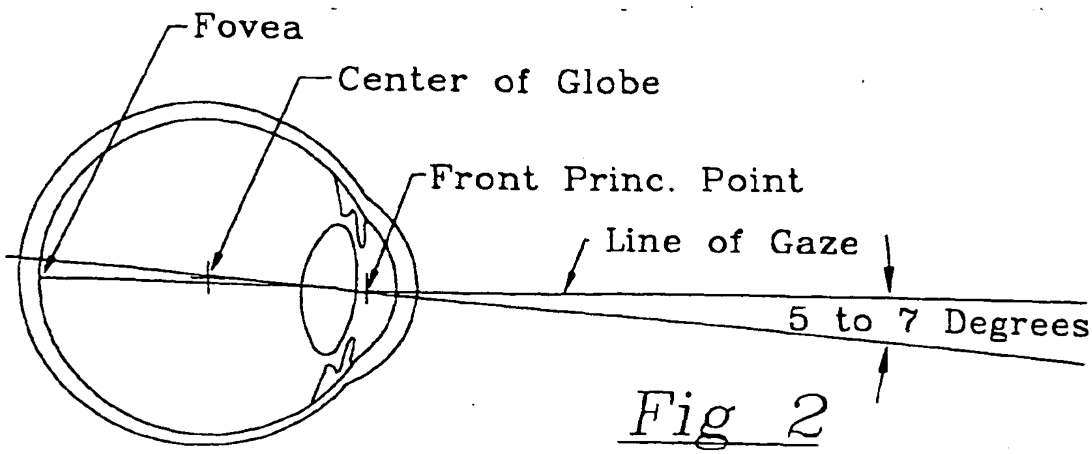
Fovea
Center of Globe
Front Princ. Point
Line of Gaze
5 to 7 Degrees

Fig 2

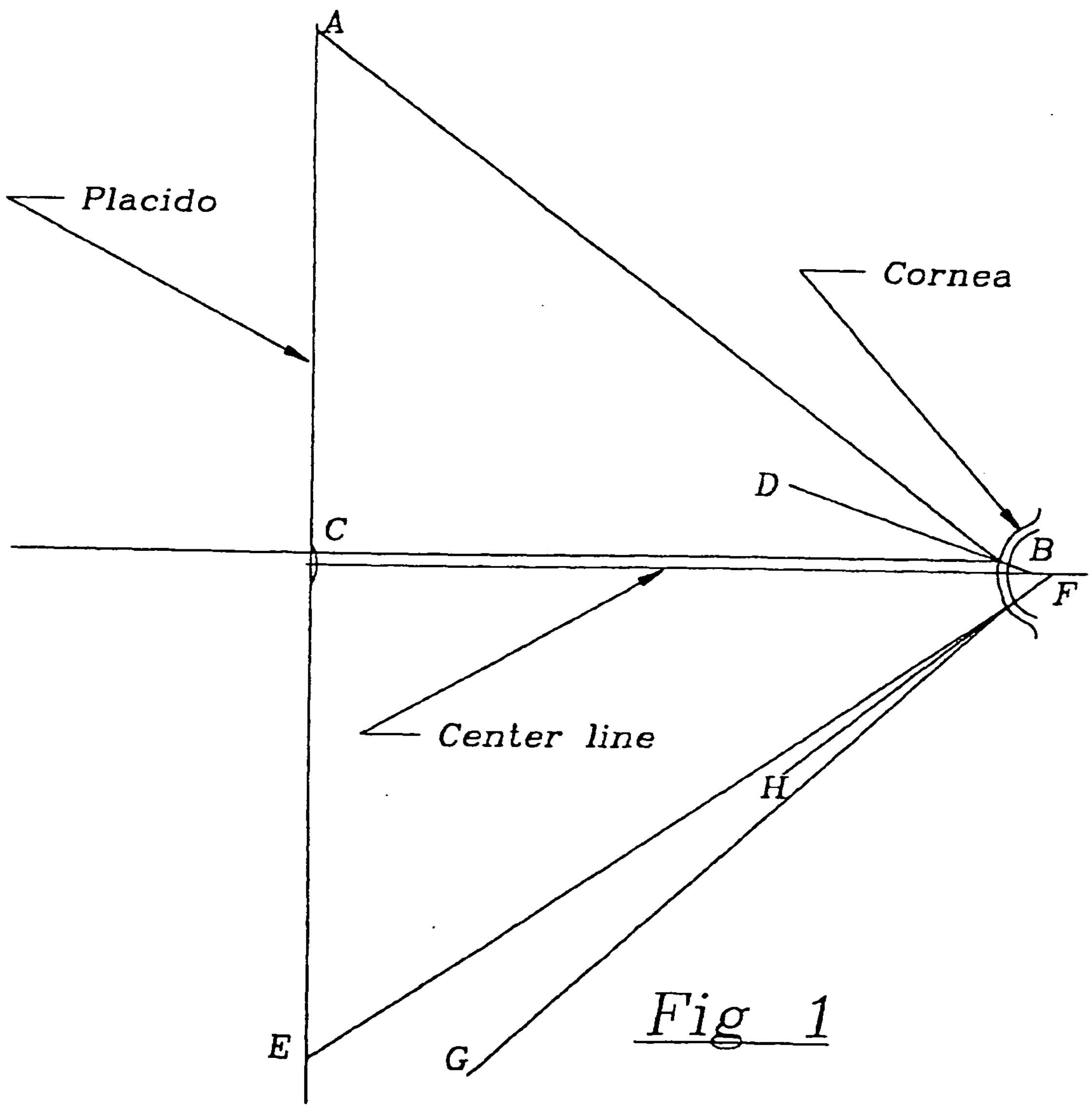
A
Placido
Cornea
D
C
B
F
Center line
H
E
G

Fig 1

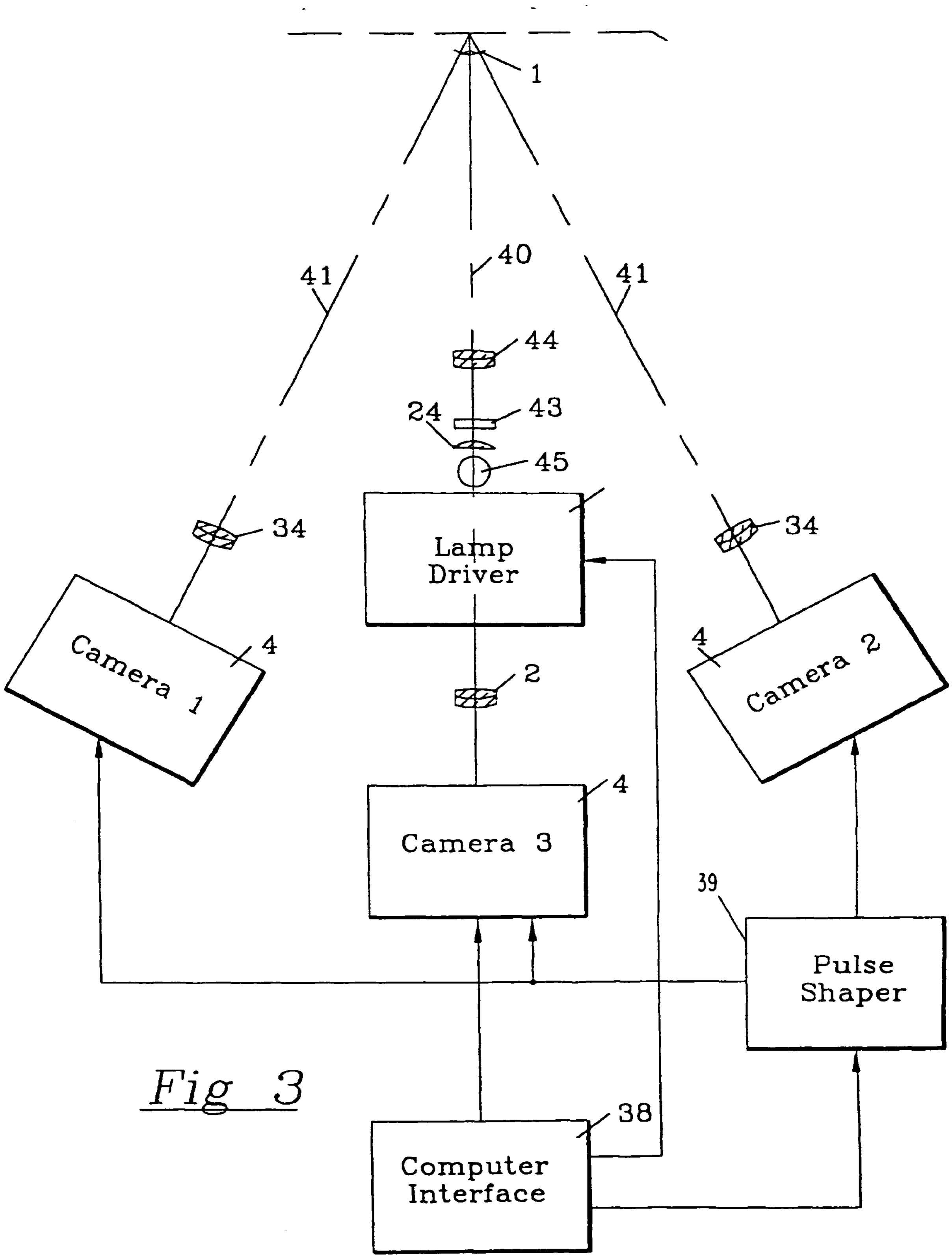
1
40
41
41
44
43
24
45
34
34
Lamp
Driver
Camera 1
4
4
Camera 2
2
4
Camera 3
39
Pulse
Shaper
38
Computer
Interface

Fig 3

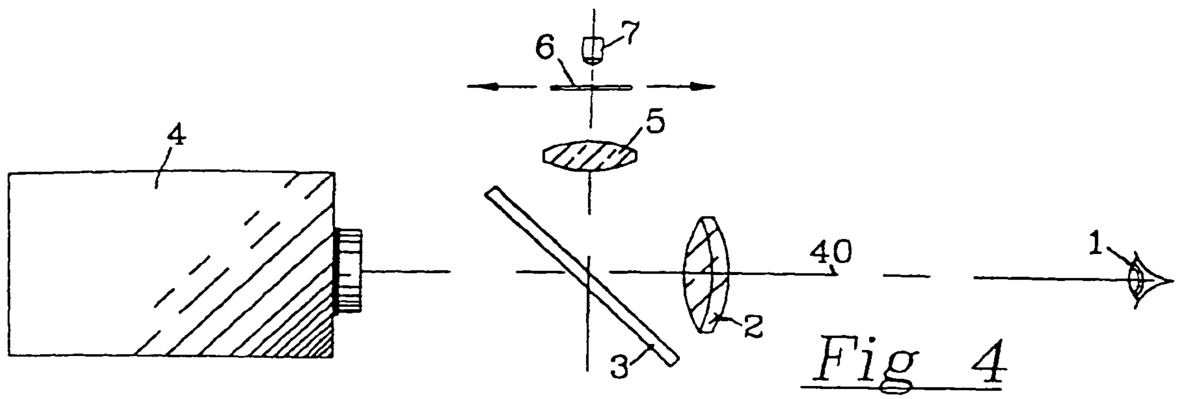


Fig 4

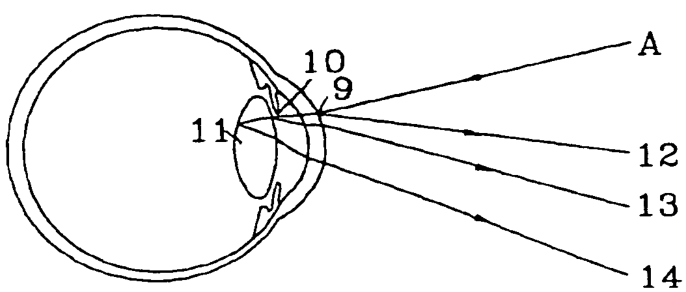


Fig 5

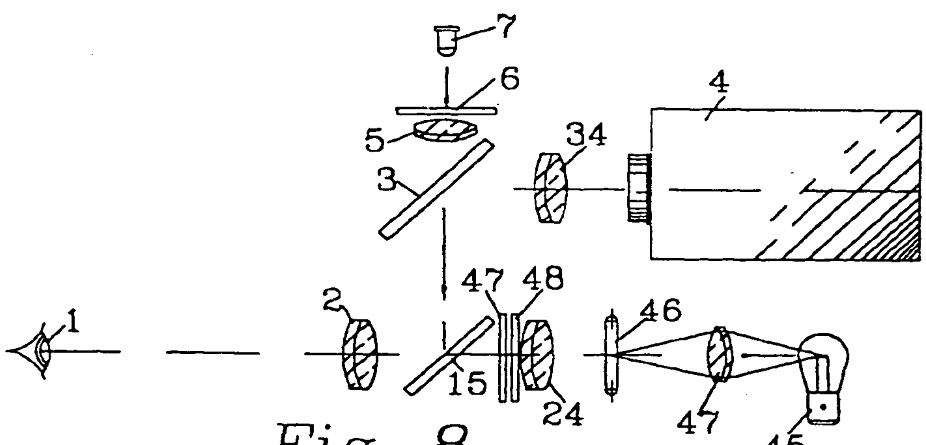


Fig 8

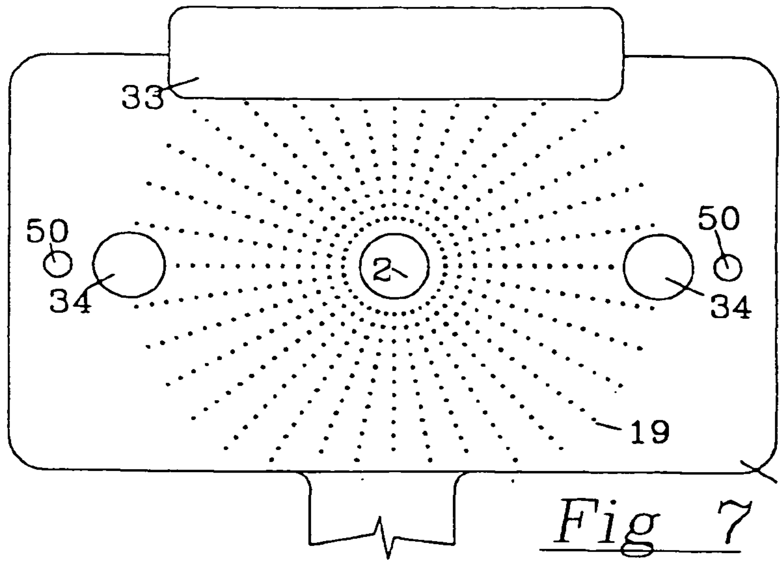
33
50
50
2
34
34
19
18

Fig 7

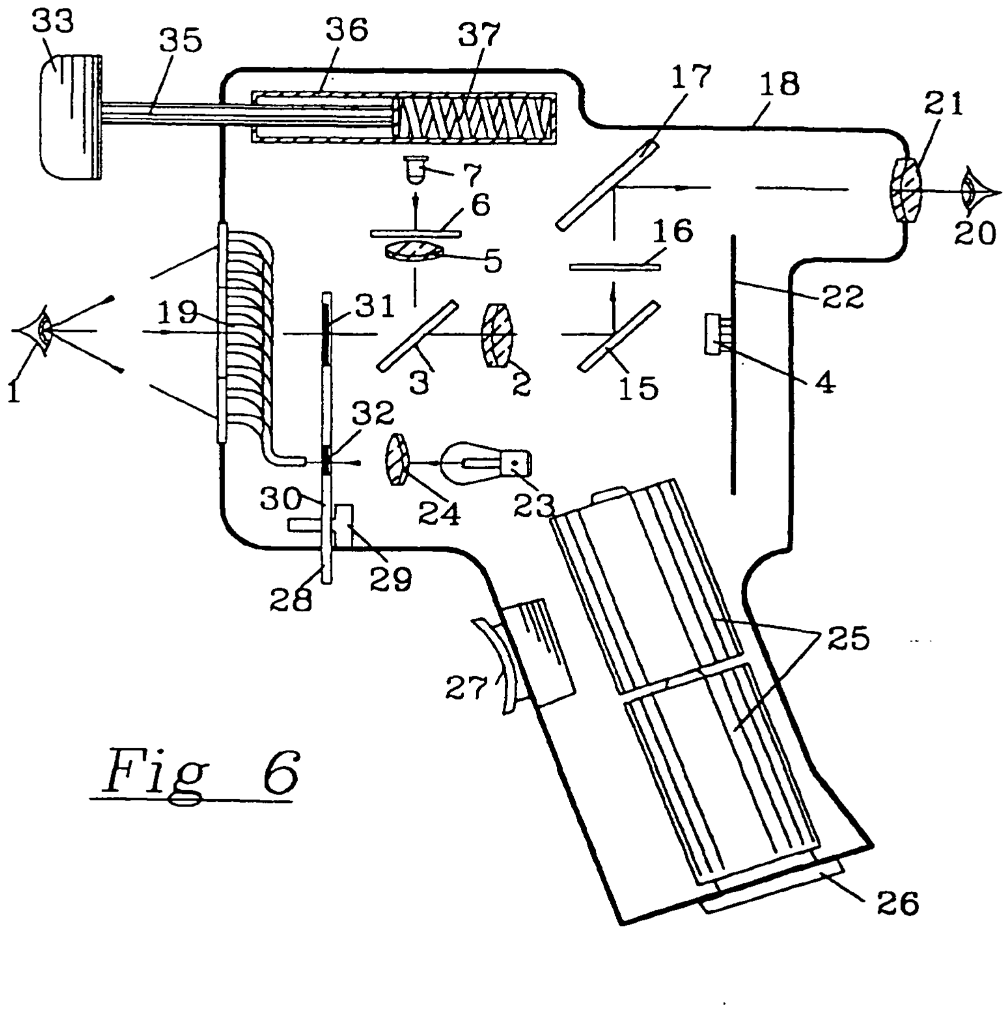
33
35
36
37
17
18
21
7
6
20
5
16
19
31
22
1
3
2
15
4
32
30
24
23
28
29
25
27
26

Fig 6

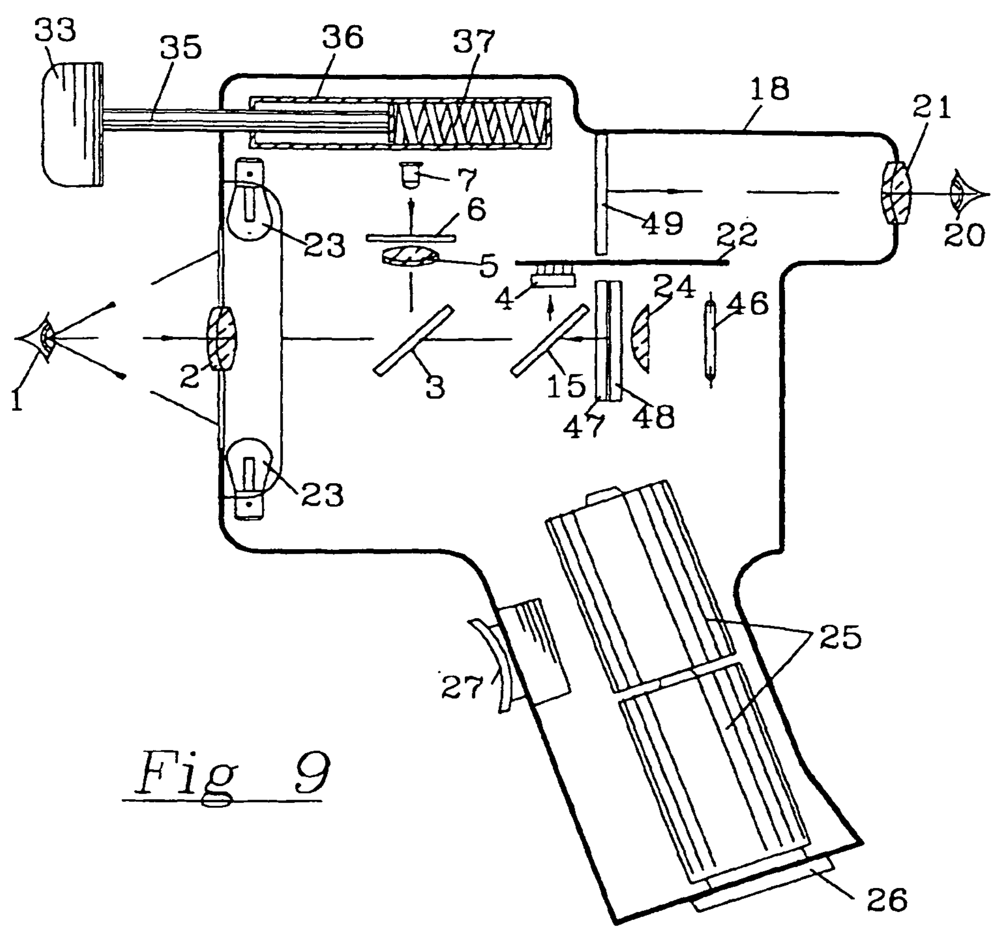


Fig 9

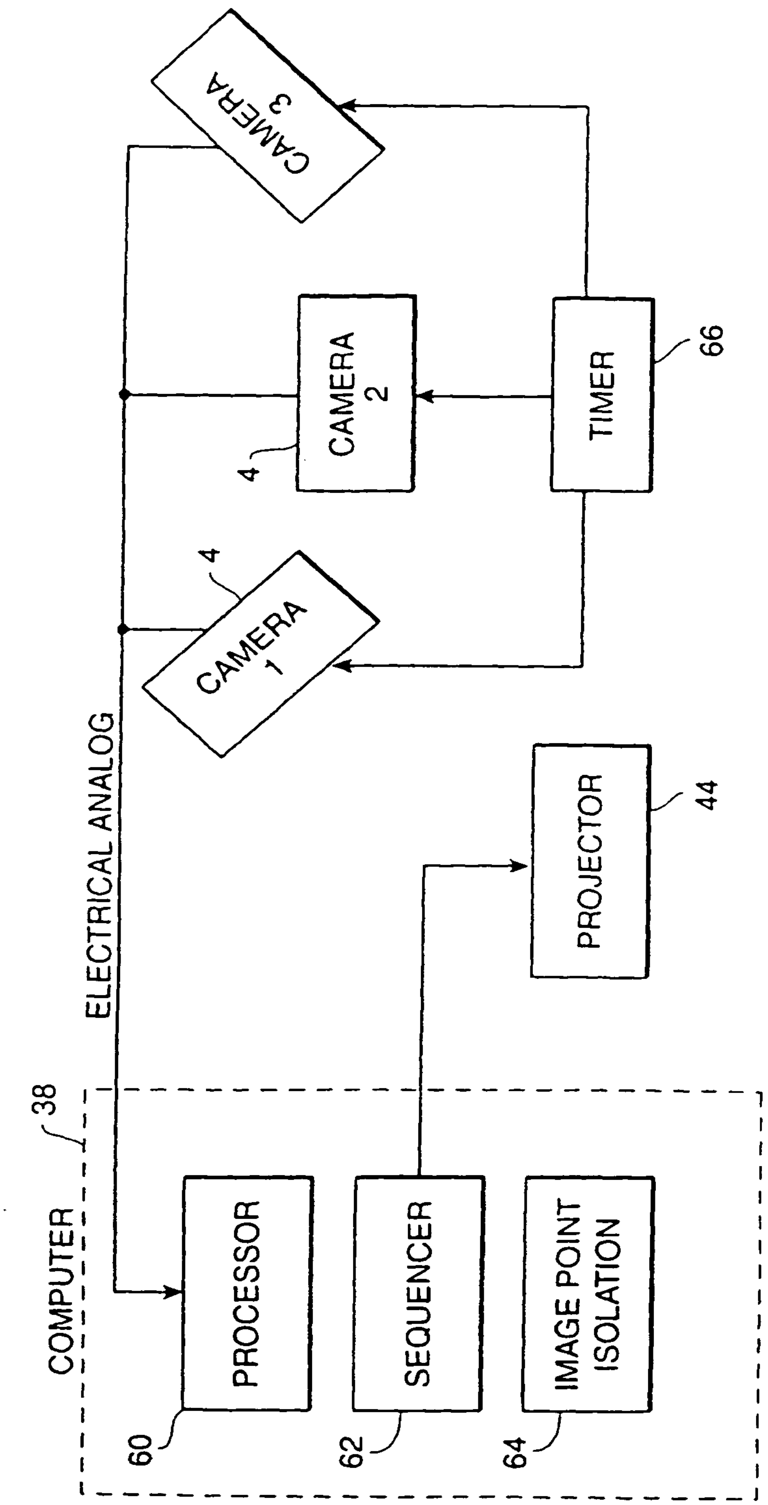
CAMERA 3
CAMERA 2
TIMER
66
4
4
CAMERA 1
ELECTRICAL ANALOG
PROJECTOR
44
38
COMPUTER
PROCESSOR
SEQUENCER
IMAGE POINT ISOLATION
60
62
64

FIG. 10

European Patent Office

# EUROPEAN SEARCH REPORT

Application Number
EP 00 10 9338

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| Category | Citation of document with indication, where appropriate, of relevant passages | Relevant to claim | CLASSIFICATION OF THE APPLICATION (Int.Cl.7) |
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The present search report has been drawn up for all claims

| Place of search | Date of completion of the search | Examiner |
|---|---|---|
| THE HAGUE | 22 September 2000 | Knüpling, M |

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X : particularly relevant if taken alone
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L : document cited for other reasons

& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

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The members are as contained in the European Patent Office EDP file on
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22-09-2000

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